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A Methodology for Developing Subject-Specific Competencies of Learners on The Basis of a Synergetic Approach (The Case of Biology)

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Abstract

This article analyzes the theoretical and practical foundations of a methodology for developing subject-specific competencies of learners in biology on the basis of a synergetic approach, together with the results of an experiment conducted to determine its pedagogical effectiveness. The study was carried out over the period 2023–2025 in eight general secondary schools of the Samarkand, Navoi, and Bukhara regions, involving a total of 697 learners, across three stages (diagnostic-prognostic, control, and formative-generalizing). The achievement levels of the experimental and control groups were analyzed using the Student–Fisher statistical criterion. The results show that implementation of the synergetic-approach methodology increased the proportion of learners with a high achievement level in the experimental group from 12.7% to 32.2%, with the statistical criterion value (Tx,y=9.28) exceeding the critical point (tkr=1.67), confirming with 95% confidence that the difference is not random. Overall teaching effectiveness increased by 13.4%.

Keywords: Synergetic approach, subject-specific competence, biology education, pedagogical experiment, Student–Fisher criterion, achievement level, teaching effectiveness, general secondary school.

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1. Introduction

In the modern education system, the development of subject-specific competencies in learners has become one of the central directions of pedagogical research. In the natural sciences, including biology education, it is considered an urgent task to form in the learner not only the mastery of ready-made knowledge but also the ability to understand complex, multicomponent systems — living organisms, ecosystems, biological processes — in a holistic and dynamic manner. The use of the methodological principles of synergetics is regarded as one of the effective approaches for accomplishing this task.

The synergetic approach is based on ideas concerning the self-organization of complex systems, the nonlinear nature of development, and the emergence of new qualitative structures as a result of the interaction among the elements of a system. When applied to the educational process, the synergetic approach makes it possible to design the learner's cognitive activity as a self-organizing, dynamic, and multi-stage process, thereby ensuring the systematic and deep mastery of biological knowledge.

The purpose of this study is to develop a methodology for the development of subject-specific competencies of learners in biology on the basis of a synergetic approach

and to determine its pedagogical effectiveness through experimental work. The objectives of the study are as follows: to organize and conduct experimental work in stages; to determine the achievement levels of the experimental and control groups; to analyze the obtained results using mathematical-statistical methods; and to scientifically substantiate the practical effectiveness of the methodology.

The scientific and practical significance of the study lies in the fact that the developed methodology and the statistical results confirming its effectiveness serve as a practical basis for improving the quality of biology teaching in general secondary schools, enhancing teachers' methodological work, and updating educational programs.

2. Literature Review and Methodology

The concept of synergetics was originally substantiated by the German physicist H. Haken as a theory of the self-organization of complex systems, and these ideas were subsequently widely applied across various fields of the natural and social sciences, including pedagogy. The theory of the self-organization of non-equilibrium systems developed by I. Prigogine and I. Stengers makes it possible to interpret the educational process as a nonlinear, multi-stage, and self-developing system.

From the perspective of pedagogical synergetics, V.I. Andreev and S.V. Kulnevich interpret the educational process as a self-organizing system arising from the collaborative activity of the learner and the teacher, in which the learner's internal reserves and activity become the decisive factor of the cognitive process. Unlike the traditional one-directional “teacher — learner” model, this approach defines the learner as an active subject who independently constructs their own system of knowledge.

From the perspective of the competency-based approach, A.V. Khutorskoy defines subject-specific competence as the learner's ability to apply, in practice, a unified set of knowledge, skills, methods of activity, and values within a particular subject domain. In biology education, the development of such competencies is manifested in the learner's ability to systematically analyze biological phenomena, formulate hypotheses, conduct observation and experimentation, and generalize the results obtained.

The methodology of the study is based on a combined application of theoretical and empirical methods. At the theoretical stage, scientific and pedagogical literature, regulatory and legal documents, instructional materials, and digital educational resources concerning the synergetic approach and competency-based education were analyzed. At the empirical stage, methods of observation, surveying, monitoring the dynamics of group behavior, and conducting experimental lessons were employed. The experimental work was conducted between 2023 and 2025 with a total of 697 learners at School No. 3 of the Pakhtachi district and School No. 66 of Kattakurgan in the Samarkand region, Schools No. 12, 15, and 20 of the city of Navoi in the Navoi region, and Schools No. 3, 18, and 5 of the Bukhara district in the Bukhara region. The obtained results were subjected to mathematical-statistical analysis using the Student–Fisher criterion.

3. Results

3.1 Organizational stages of the pedagogical experimental work

In the course of the study, experimental work on the topic “Developing subject-specific competencies of learners on the basis of a synergetic approach (the case of biology)” was organized using the following methods: the study of scientific and theoretical literature on pedagogy and methodology, the critical analysis and synthesis of existing curricula and textbooks, observation, surveying, monitoring the dynamics of behavior, studying and generalizing experience, and conducting experimental lessons. The investigation of the problem of developing learners' subject-specific competencies on the basis of a synergetic approach in the experimental sites was carried out in three stages over the period from 2023 to 2025.

During the first stage of the experimental work — the diagnostic and prognostic stage (2023) — regulatory and legal documents, scientific sources, instructional and educational literature, electronic educational resources, and information-educational environments relevant to the research topic were analyzed; the relevance and necessity of the topic were studied; and the purpose, objectives, object, subject, and methods of the research were determined.

During the second stage — the control stage (2023–2024) — the survey questions were refined, the work carried out during the first stage was analyzed, additional information on methods of developing learners' subject-specific competencies in biology on the basis of a

synergetic approach was collected from education systems around the world, conversations were held with learners, and their interest in the problem under investigation was studied.

During the third stage — the formative and generalizing stage (2024–2025) — the scientific and methodological foundations for updating the content of the subject and improving teaching methodology were examined; the experimental data were processed; conclusions and scientific generalizations were formulated; and, with the curricula refined, didactic support for the development of learners' subject-specific competencies on the basis of a synergetic approach was developed. The materials of the experimental work were collected, edited, generalized, summarized, and analyzed using mathematical-statistical methods.

In order to ensure the objectivity of the experimental work, two parallel groups — an experimental group and a control group — were designated for each academic year. In the control groups, the educational process was organized according to the conventional teaching methodology (listening to lectures, performing practical and laboratory assignments, independent work), while in the experimental groups it was organized using the methods developed on the basis of the synergetic approach.

3.2. Results of the experimental work by region

A total of 697 learners were involved in the pedagogical experimental work: 218 from School No. 3 of the Pakhtachi district and School No. 66 of Kattakurgan in the Samarkand region, 190 from Schools No. 12, 15, and 20 of the city of Navoi in the Navoi region, and 289 from Schools No. 3, 18, and 5 of the Bukhara district in the Bukhara region. Learners' readiness for biology education was assessed on the basis of three levels — high, medium, and low.

According to the results of the experimental work conducted in the Samarkand region, in the 105-member experimental group the proportion of learners with a high achievement level rose from 12.4% at the beginning of the experiment to 32.4% by its conclusion — an increase of nearly two and a half times. At the same time, in the 113-member control group this indicator rose only from 12.4% to 13.3%, indicating that the difference between the two groups arose under the influence of the synergetic approach (Table 1).

Table 1.

Results of the pedagogical experimental work conducted at School No. 3 of the Pakhtachi district and School No. 66 of Kattakurgan, Samarkand region

Indicator	Start of experiment (no./%)	End of experiment (no./%)	Control: start (no./%)	Control: end (no./%)
High	13 / 12.4%	**34 / 32.4%**	14 / 12.4%	15 / 13.3%
Medium	42 / 40%	**53 / 50.5%**	45 / 39.8%	47 / 41.6%
Low	50 / 47.6%	**18 / 17.1%**	54 / 47.8%	51 / 45.1%

A similar trend was observed in the results of the experimental work conducted at Schools No. 12, 15, and 20 in the city of Navoi: in the 94-member experimental group, the proportion with a high achievement level rose from 16% to 35.1%, whereas in the 96-member control group this indicator remained virtually unchanged (16.7% to 16.7%) (Table 2).

Table 2.

Results of the pedagogical experimental work conducted at Schools No. 12, 15, and 20 in the city of Navoi, Navoi region

Indicator	Start of experiment (no./%)	End of experiment (no./%)	Control: start (no./%)	Control: end (no./%)
High	15 / 16%	**33 / 35.1%**	16 / 16.7%	16 / 16.7%
Medium	42 / 44.7%	**51 / 54.3%**	43 / 44.8%	45 / 46.9%
Low	37 / 39.3%	**10 / 10.6%**	37 / 38.5%	35 / 36.4%

The results of the experimental work conducted at Schools No. 3, 18, and 5 of the Bukhara district, Bukhara region, are distinguished from the other regions by a higher initial proportion of low achievers (60%); nevertheless, by the conclusion of the experiment, the proportion with a high achievement level in the 140-member experimental group rose from 10.7% to 30% — nearly a threefold increase — whereas in the 149-member control group this indicator changed only from 11.4% to 12.1% (Table 3).

Table 3.

Results of the pedagogical experimental work conducted at Schools No. 3, 18, and 5 of the Bukhara district, Bukhara region

Indicator	Start of experiment (no./%)	End of experiment (no./%)	Control: start (no./%)	Control: end (no./%)
High	15 / 10.7%	**42 / 30%**	17 / 11.4%	18 / 12.1%
Medium	41 / 29.3%	**69 / 49.3%**	44 / 29.5%	47 / 31.5%
Low	84 / 60%	**29 / 20.7%**	88 / 59.1%	84 / 56.4%

The generalized results across all general secondary schools show that, in the 339-member experimental group, the proportion with a high achievement level rose from 12.7% to 32.2% (an increase of +19.5 percentage points), the medium level rose from 36.9% to 51%, and the low level fell sharply from 50.4% to 16.8%. In the 358-member control group over the same period, the high level changed only from 13.1% to 13.7%, the medium level from 36.9% to 38.8%, and the low level decreased from 50% to 47.5% — a change considerably smaller than that observed in the experimental group (Table 4).

Table 4.

Generalized results of the pedagogical experimental work across all general secondary schools

Indicator	Start of experiment (no./%)	End of experiment (no./%)	Control: start (no./%)	Control: end (no./%)
High	43 / 12.7%	**109 / 32.2%**	47 / 13.1%	49 / 13.7%
Medium	125 / 36.9%	**173 / 51%**	132 / 36.9%	139 / 38.8%
Low	171 / 50.4%	**57 / 16.8%**	179 / 50%	170 / 47.5%

3.3. Mathematical-statistical analysis of the results

In order to ensure the reliability of the experimental results, the average achievement indicators of the experimental and control groups were analyzed using the Student–Fisher mathematical-statistical method. A total of 697 learners participated in the experimental work, of whom 339 constituted the experimental group and 358 the control group.

At the start of the experiment, designating the experimental and control groups conditionally as Sample 1 and Sample 2, the following variation series were obtained: in the experimental group (m=339), high level — 43, medium — 125, low — 171; in the control group (n=358), high level — 47, medium — 132, low — 179 (Table 5). At the initial stage, the indicators of the two groups were nearly identical, confirming that the experimental and control groups were equivalent at the outset and thereby ensuring the reliability of the results to be obtained at the subsequent stage.

Table 5.

Achievement-level indicators of respondents in the experimental and control groups at the start of the experiment

Groups	Number of respondents	High	Medium	Low
Experimental group	339	43	125	171
Control group	358	47	132	179

The percentage indicators of achievement levels were calculated using the following formula:

$$K = (J / Q) \times 100\% \qquad (1)$$

where J is the number of correct answers given by learners in the surveys conducted during the experimental work, and Q is the total number of learners in the experimental or control group whose results are being considered.

The results obtained at the conclusion of the experiment are presented in Table 6: in the 339-member experimental group, the high level rose to 109, the medium level to 173, and the low level fell to 57; in the 358-member control group, the high level reached only 49, the medium level 139, and the low level remained at 170.

Table 6.

Achievement-level indicators of respondents in the experimental and control groups at the conclusion of the experiment

Groups	Number of respondents	High	Medium	Low
Experimental group	339	**109**	**173**	**57**
Control group	358	49	139	170

Based on the results at the conclusion of the experiment, Sample 1 (experimental group, m=339): high — 109, medium — 173, low — 57; Sample 2 (control group, n=358): high — 49, medium — 139, low — 170. According to the constructed diagrams, the mean values of the results correspondingly satisfy the condition X>Y, confirming that the average achievement indicator of the experimental group exceeds that of the control group.

In order to determine the dispersion coefficients of the two groups, the variance values and standard deviations of the samples were calculated, after which the variation indicators for the experimental and control groups were determined. With the significance level of the mathematical-statistical criterion set at α=0.05, the critical point for the statistic, determined from the Laplace table, was found to equal tkr=1.67. The calculated Student sample criterion was found to be Tx,y=9.28, a value considerably greater than the critical point (1.67).

Consequently, the null hypothesis (H0) of the equality of the population means is rejected. It can therefore be stated, with 95% confidence, that the average achievement indicators of the experimental group were consistently higher than those of the control group, and that the two never overlapped. To determine the confidence interval of the estimate, the values Δm≈0.047 for the experimental group and Δn≈0.078 for the control group were calculated. The geometric representation of the resulting confidence intervals shows that the difference at the α=0.05 significance level is sufficient, with the average evaluation indicators of the experimental-group learners exceeding those of the control group and the intervals not overlapping in the graph. This confirms that the result of the mathematical-statistical analysis is precise and highly reliable.

4. Discussion

The statistical results obtained demonstrate that the methodology developed on the basis of the synergetic approach possesses high pedagogical effectiveness in the teaching of biology. The nearly two-and-a-half-fold increase in the proportion of high achievers in the experimental group (from 12.7% to 32.2%) and the sharp decrease in the proportion of low achievers (from 50.4% to 16.8%) attest to a substantial increase in learners' ability to master biological knowledge systematically and deeply.

The results of the regional analysis confirm that the methodology demonstrates stable effectiveness even under different socio-educational conditions: even in the schools of the Bukhara region, where the initial achievement level was relatively low (an initial low-level proportion of 60%), the experimental group showed an increase of nearly threefold in the high-achievement level, demonstrating the methodology's adaptability to varying initial conditions.

The fact that the value Tx,y=9.28, obtained on the basis of the Student–Fisher criterion, is considerably higher than the critical point tkr=1.67, and that the confidence intervals do not overlap in the graph, ensures the high statistical reliability of the results. The 13.4% increase in overall teaching effectiveness provides a scientific basis for the practical implementation of the methodology and demonstrates the possibility of its application in other general education institutions.

5. Conclusion

Based on the results of the study conducted, the following conclusions were reached:

1) A methodology for developing learners' subject-

specific competencies in biology on the basis of a synergetic approach was developed as a three-stage system comprising diagnostic-prognostic, control, and formative-generalizing stages, and was tested over the period 2023–2025 in eight general secondary schools of the Samarkand, Navoi, and Bukhara regions.

2) A total of 697 learners (339 in the experimental group and 358 in the control group) participated in the experimental work. Across all regions, the proportion of high achievers in the experimental group rose from 12.7% to 32.2%, whereas in the control group this indicator remained practically unchanged (from 13.1% to 13.7%).

3) According to the results of the analysis conducted using the Student–Fisher mathematical-statistical criterion, the calculated statistic value was Tx,y=9.28, considerably exceeding the critical point tkr=1.67, which proves that the difference is not random at a 95% confidence level.

4) On the basis of the experimental results, it was determined that the teaching effectiveness of the proposed methodology, based on the synergetic approach, increased by 13.4% relative to the control group, confirming the practical effectiveness of the methodology.

5) The results of the study provide a basis for the broad implementation of the synergetic approach in biology education and for the development of practical recommendations for improving teachers' methodological training and updating didactic materials.

In conclusion, it should be emphasized that the synergetic approach in biology education makes it possible to design the learner's cognitive activity as a self-organizing, dynamic process, thereby ensuring the highly effective formation of subject-specific competencies. In future research, it would be promising to extend this methodology to other natural sciences (chemistry, physics, geography) and to integrate it with digital educational tools.

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